Can we link theory to observations in natural flows?

Andrea Cimatoribus

ÃĽcole Polytechnique FÃľdÃľrale de Lausanne

PSI, 14 February 2017

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

CV in one slide

What	When
Batchelor in Chemistry (Uni Trieste, IT)	2001-2005
Internship at INOGS (IT)	2005
Master in Physics (Uni Trieste, IT)	2005-2008
Internship at Elettra Synchrothron (IT)	2008
PhD at KNMI/Uni Utrecht (NL)	2009-2013
Post-doc at NIOZ (NL)	2013-2016
Post-doc at EPFL (CH)	2016-2018

- 17 peer-reviewed papers and proceedings
- Lots of (open-source) software
- Several datasets collected
- Conferences, workshops (EGU, Euromech,...)
- Summer schools: DAMTP Cambridge, Alpine Summer School

Turbulence and internal waves in geophysical flows

- Can we link theory to observations?

An overview of my work at NIOZ and EPFL

A statistical perspective on fluid motions

Context: Increasing *amount* and *quality* of observational data.

Opportunity to obtain a *"statistical"* description.

- Focus on full dataset instead of single events.
- In practice: spectra, structure functions, PDFs, PCA,…

A statistical perspective on fluid motions

Statistics of temperature, velocity,...

- scale-dependence of variability;
- intermittency (e.g., time/space dispersion of turbulence events);
- hints on underlying physical mechanisms;
- identification of different regimes at different scales.

A statistical perspective on fluid motions

Statistics of temperature, velocity,...

- scale-dependence of variability;
- intermittency (e.g., time/space dispersion of turbulence events);
- hints on underlying physical mechanisms;
- identification of different regimes at different scales.

Well-established field (IWs, turbulence):

- relatively well understood theory (single-process level);
- laboratory studies.

A statistical perspective on fluid motions

Statistics of temperature, velocity,...

- scale-dependence of variability;
- intermittency (e.g., time/space dispersion of turbulence events);
- hints on underlying physical mechanisms;
- identification of different regimes at different scales.

Well-established field (IWs, turbulence):

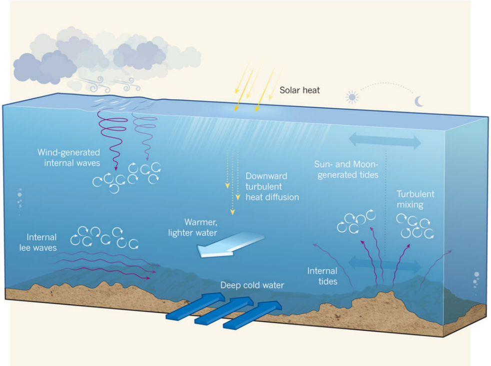
- relatively well understood theory (single-process level);
- laboratory studies.

In the field:

- We cannot control what we observe in the field,
  - e.g. control parameters are variable / undefined.
- Statistics can help extracting information from "noisy" data.

Turbulent transport in the deep ocean (NIOZ)

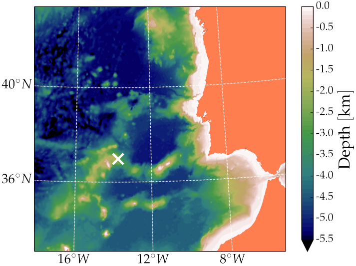
- Vertical transport in the ocean interior is poorly understood
- Hypothesis of mixing "hot-spots" with sloping bottom
- Sparse observations, poorly understood dynamics



MacKinnon, 2013

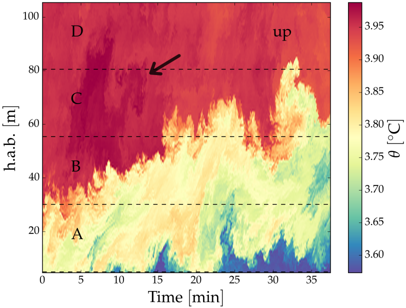
Data

Latitude	36° 58.885′ N
Longitude	13° 45.523′ W
Max. depth	2205 m
Min. height above seafloor	5 m
Seafloor slope	9.4°
Number of sensors	144
Vertical spacing	0.7 m
Depth range	100.1 m
Deployment	13 Apr 2013
Recovery	12 Ago 2013
Sampling rate	1 Hz

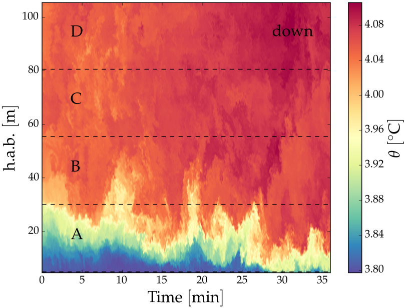


Data

Cooling phase (upslope)



Warming phase (downslope)



Generalised structure functions (GSF)

GSFs provide a way to characterise variability in a flow:

$$\gamma_q \equiv \gamma_q(r) = \left\langle |\Delta_r \theta|^q \right\rangle$$

So-called "scaling ranges" have been predicted by theory and observed in the laboratory:

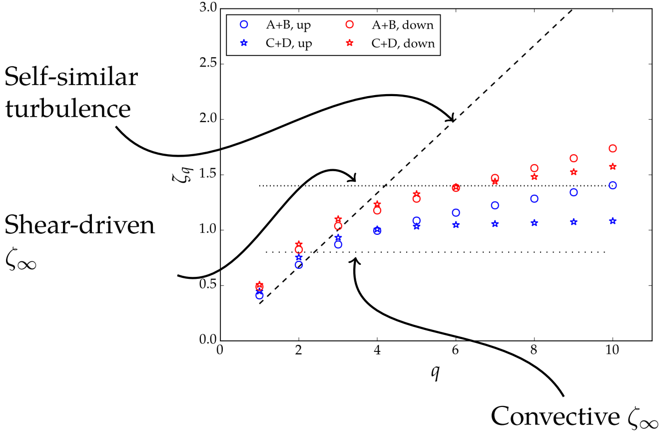
$$\gamma_q \sim r^{\zeta(q)}.$$

- $\zeta(q) = q/3$ if turbulence were fully self-similar (non-intermittent), for r within the "turbulence inertial range".
- In reality, $\zeta(q) = \zeta_\infty$ for $q > 10$ (*saturation*):
  - Grid turbulence, shear driven $\rightarrow \zeta_\infty \approx 1.4$
  - Convective turbulence, buoyancy driven $\rightarrow \zeta_\infty \approx 0.8$

Generalised structure functions (GSF)

...many steps afterwards...

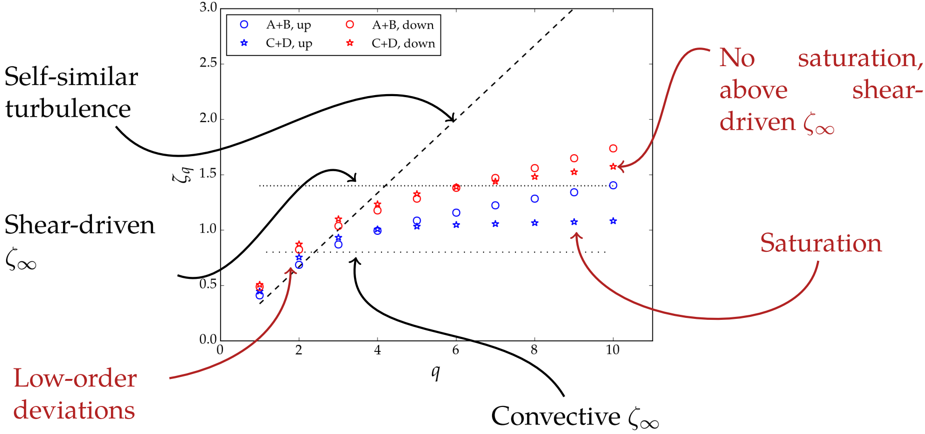
Scaling exponent within the turbulence inertial range.



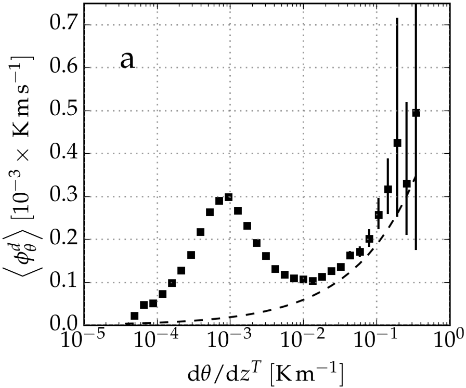
Generalised structure functions (GSF)

…many steps afterwards…

Scaling exponent within the turbulence inertial range.



Flux–gradient relation



Long-term averaging enables to identify simple *mean* behaviour in an otherwise highly variable environment.

Conclusions I

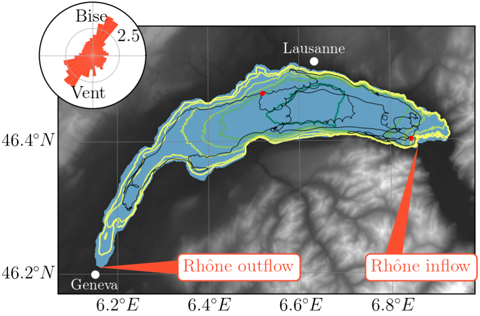
Evidence of convection in field observations

- Previously hypothesised, but hard to measure.
- Implications for efficiency of turbulent transport:
  - Implications for transport of heat, CO_2, nutrients,…
- Generalised structure functions enable to identify points of contact between laboratory and field results…
- …and discrepancies!
- *Much more not shown here.*

- A. A. Cimatoribus and H. van Haren. Temperature statistics above a deep-ocean sloping boundary. *J. Fluid Mech.*, 775:415–435, 2015.
- A. A. Cimatoribus and H. van Haren. Estimates of the temperature flux–temperature gradient relation above a sea floor. *J. Fluid Mech.*, 793:504–523, 2016.

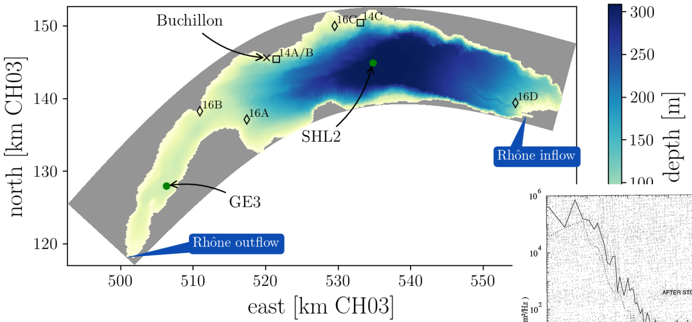
Transport in coastal areas (EPFL)

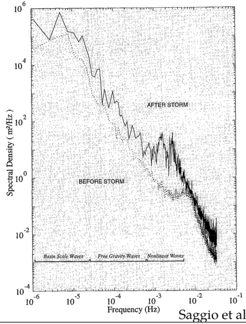
- In a linear, rotating flow, cross-isobath velocity is zero.
- How does cross-shore transport take place?



Velocity spectra

Lake Geneva





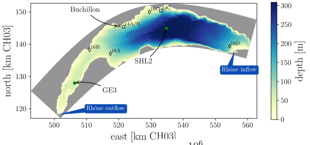
Saggio et al., 1998

“Standard” interpretation of observations:

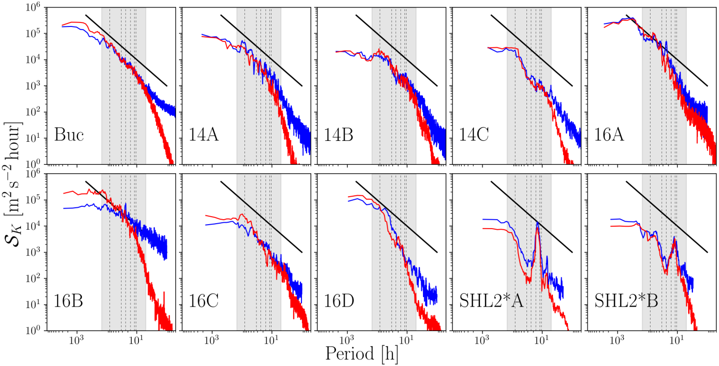
- combination of long internal waves (seiches)
- linear or weakly nonlinear

Velocity spectra

Lake Geneva



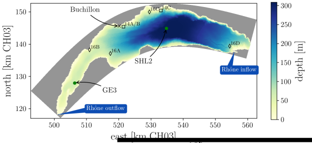
Kinetic energy spectra



Observations, model, slope = -1, dashed lines: linear modes frequencies

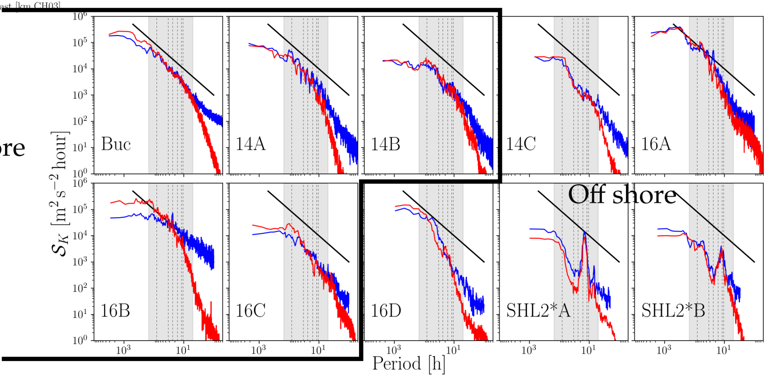
Velocity spectra

Lake Geneva



Kinetic energy spectra

Near shore



Observations, model, slope = -1, dashed lines: linear modes frequencies

Conclusions II

Nonlinearity cannot be neglected.

- Linear models predict sharp spectra, which are only observed off-shore,
  - or by considering short time intervals
- Broad spectra from longer time series suggest strongly nonlinear dynamics (more “turbulence”-like)
  - Confirmed by numerical modelling results.
- Classical tools like PCA, struggle to capture relevant dynamics in the highly variable, strongly forced, Lake Geneva.

- Andrea A. Cimatoribus, U. Lemmin, D. Bouffard, and D. A. Barry. Nonlinear Dynamics of the Nearshore Boundary Layer of a Large Lake (Lake Geneva). *J. Geophys. Res. Oceans*, in press, 2018.

Conclusions

- Field observations are growing in size and quality.
- A statistical description allows testing theories in a natural (uncontrolled) environment,
  - whose overall, mean behaviour is usually the most interesting one.
- Sometimes, statistical quantities can surprise:
  - Simple behaviour out of highly turbulent environments
  - Nonlinear behaviour (instabilities? vortices?) in a low energy environment
    - from very common power spectra!

Thanks for listening.

Andrea.Cimatoribus@epfl.ch

[La Palma, Islas Canarias]